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FINAL REPORT

STUDY OF STORM TIME FLUXES
OF HEAVY IONS

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SECTION 1

INTRODUCTION

The central focus of this program has been the investigation of the characteristics of the stormtime ring current ions in the energy range of 0.5 to 16 keV. Data were processed and analyzed from the Lockheed energetic ion mass spectrometer aboard the S3-3 satellite which was launched into a polar orbit in July 1976 and is still operating. Results from this program have also served as a valuable guide for planning and operating the ion mass spectrometer experiment on the ISEE spacecraft, for selecting and processing the ISEE ion data (Johnson, et al., 1978), and for planning and conducting coordinated satellite experiments in support of the International Magnetospheric Study (IMS).

It is now well established from the S3-3 ion data that relatively large fluxes of energetic (keV) O^+ and H^+ ions are frequently flowing upward from the ionosphere along magnetic field lines in the polar auroral regions [Shelley, et al., 1976, Sharp et al. 1976, and Ghielmetti et al., 1978]. Also, from investigations with the same instrument during the main phase of three moderate ($D_{ST} \sim 100$) magnetic storms, it was found that the number density of O^+ ions in the ring current was comparable to H^+ ion density in the range 0.5 to 16 keV [Johnson et al., 1977].

In addition to an improved understanding of the general morphology of the ring current ions, the present study has also identified two new features that appear to be important in understanding the ring current development:

- 1) Solar wind ions have been observed during two magnetic storms at low L-shells during the main phase of ring current development; and
- 2) Upstreaming conical ions distributions are observed at low L-shells ($L=4-5$) may be an important source of the ionospheric ions observed in the inner ring current.

To investigate the general characteristics of the ring current ions during moderate ($D_{ST} \sim 100$) magnetic storms, the 29 July 1977 storm has been studied in considerable detail. The 15 February 1978 storm has been investigated to provide additional data on the new features discussed above, and several storms have been investigated in a preliminary fashion to look for storm-to-storm variability and to support some of the IMS activities, particularly the time period in December 1978 which was selected by the IMS Steering Committee for detailed coordinated investigations.

For this report, the data for the individual storms are presented and discussed separately. The general discussion and conclusions are then presented in the final section of this report.

The ion composition measurements used in this study were made with an energetic ion mass spectrometer aboard the polar-orbiting S3-3 spacecraft which has perigee near 350 km and apogee near 8000 km. The spacecraft is spinning at 3 rpm with the spin axis normal to the orbital plane and with

the instrument view directions in the orbital plane. The instrument contains 3 ion mass spectrometers and 4 electron spectrometers whose designs have been described previously [Shelley, et al., 1972; Reed et al., 1969]. Each ion spectrometer acquires a 30-channel mass-per-unit-charge spectrum every second. Every 16 seconds the energy-per-unit-charge setting for each spectrometer is stepped to one of the four values, allowing a 12-point energy spectrum to be acquired every 64 seconds. Each spectrometer on Step 1 is in the lowest energy step, etc. The energy-per-unit-charge values are 0.5, 0.68, 0.94, and 1.28 keV for spectrometer #1; 1.76, 2.4, 3.3, and 4.5 keV for spectrometer #2; and 6.2, 8.5, 11.6, and 16.0 keV for spectrometer #3. The four broadband electron channels span the energy ranges 0.07 to 0.24 keV, 0.35 to 1.1 keV, 1.6 to 5.0 keV, and 7.3 to 24 keV.

SECTION 2
29 JULY 1977 MAGNETIC STORM

Excellent data coverage near apogee of the S3-3 satellite was obtained throughout the magnetic storm on 29 July 1977. Satellite apogee was in the local time sector near 0500 hours and the ring current data presented here were obtained at altitudes in the range 7000-8000 km. A plot of Dst for this storm is shown in Figure 1 along with three other storms of comparable magnetude which had been investigated earlier for the ring current ion composition [Johnson et. al., 1977]. The peak of main phase in each storm is seen to be about -100γ . The very low and nearly constant Dst for 3 days prior to the 29 July storm and the relatively smooth transition to the peak of the main phase of the storm may make this event a good one for more detailed study by the IMS community. The S3-3 coverage for the main phase portion and for the early decay phase of the 29 July storm is shown in Figure 2. From this plot it can be seen that the main phase was followed by a relatively rapid decay phase until about 1000 hours U.T. when a second enhancement of the ring current occurred. A large substorm, which was widespread in local time, was observed near 1200 hours in the ground-based magnetograms.

Examples of the ion mass spectra in three different energy ranges for two different L-shell regions during REV 3120 near the peak of Dst (see Figure 2) are shown in Figure 3. This shows the good signal-to-background ratio throughout the region $L=2.58$ to 4.0 . The background counting rates were even lower at the higher latitudes. The region $L=2.58-3.02$ was near the inner edge of the ring current fluxes and the relatively large O^+ fluxes in all

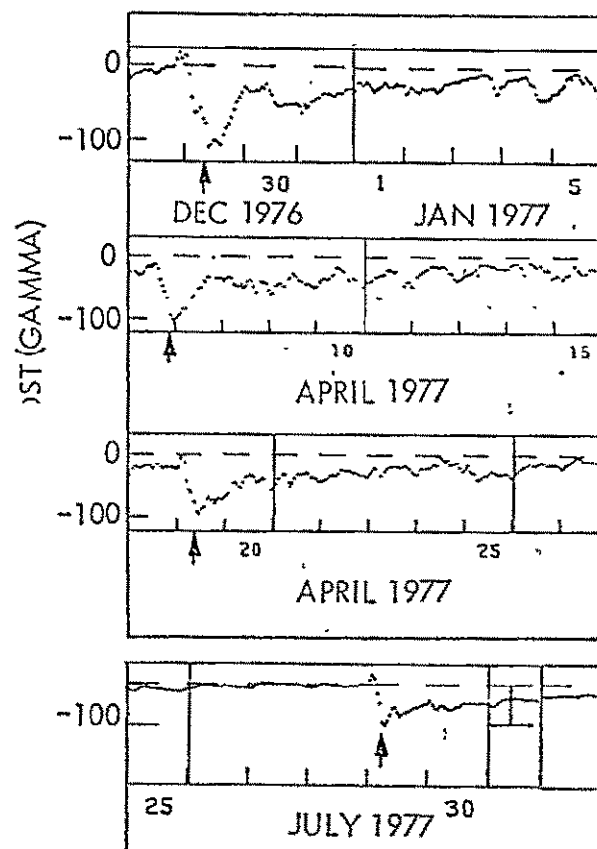


Figure 1. D_{ST} for Four Magnetic Storms of Comparable Peak Intensities.

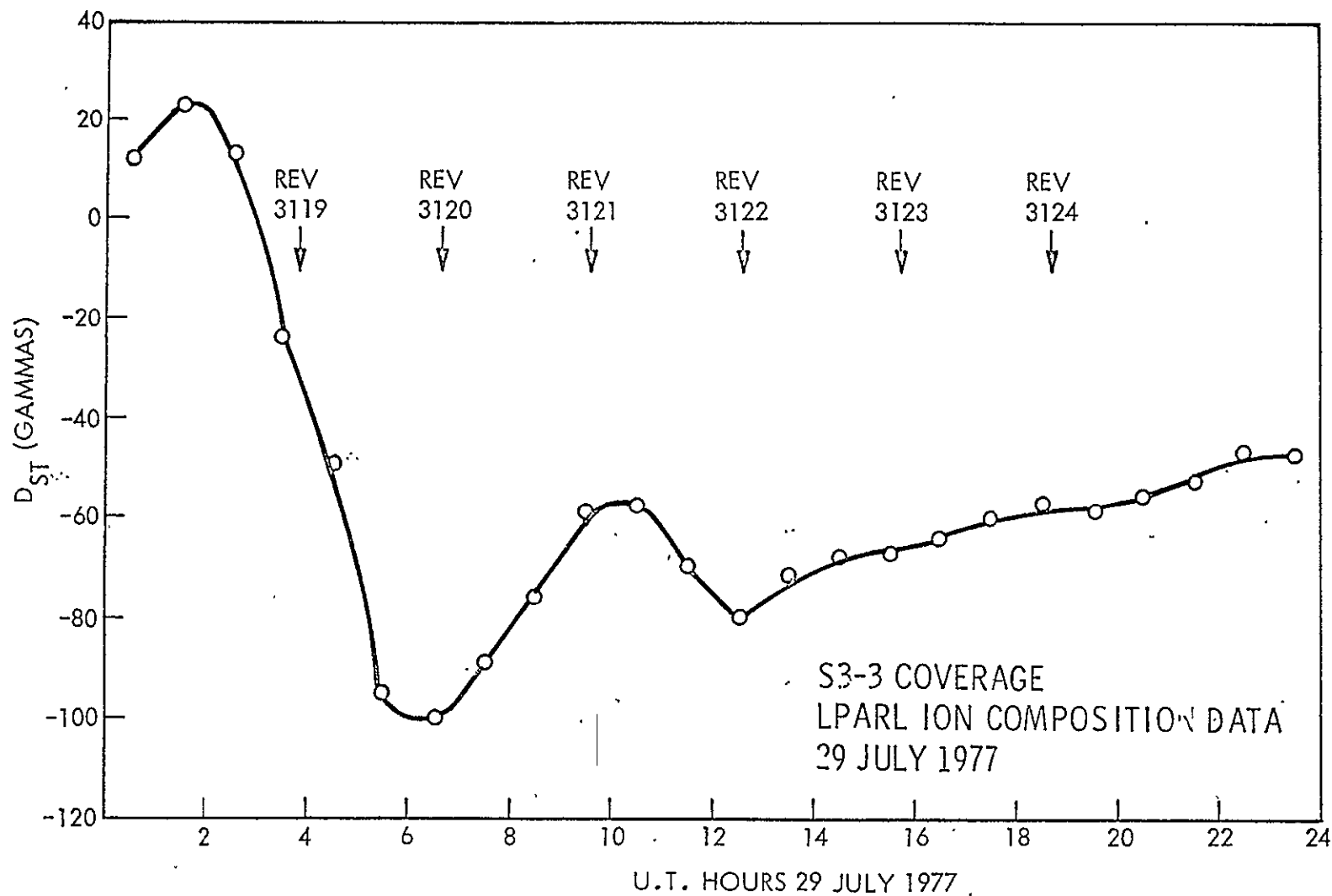


Figure 2. The Location of S3-3 Satellite Coverage During the 29 July 1977 Magnetic Storm.

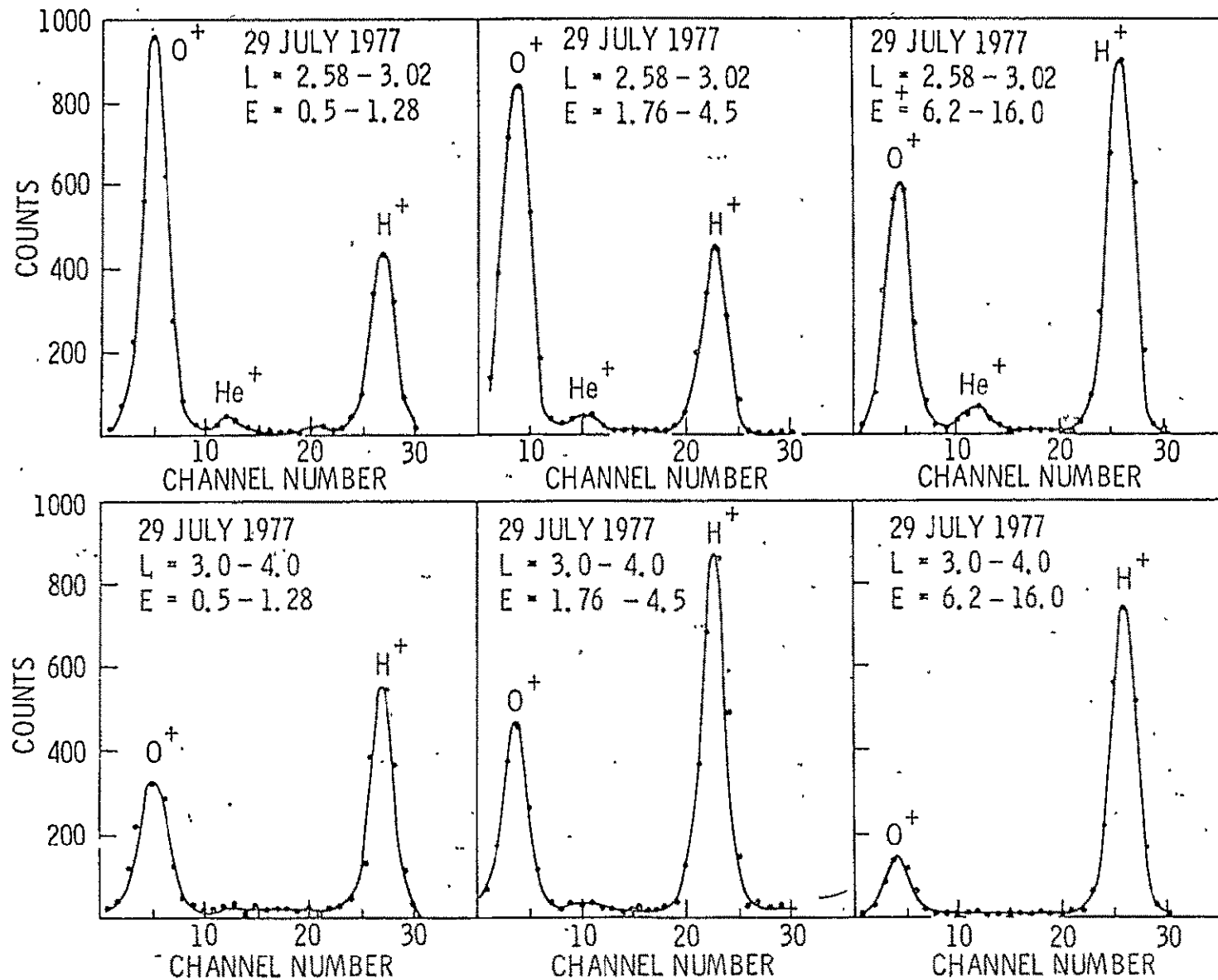


Figure 3. Mass Spectra Near the Peak D_{ST} During the 29 July 1977 Magnetic Storm.

three energy regions can be seen. In the region $L=3.0-4.0$ significantly lower O^+ fluxes are observed, particularly at the higher energies.

The L-shell distribution of the O^+ and H^+ ion number densities in the instrument energy range 0.5-16 keV are shown for REV 3120 in Figure 4. Also shown are the densities observed with the same instrument in the local morning sector (02.2 hours) during the 29 December 1976 magnetic storm. For the 29 July storm, particularly large O^+/H^+ ratios are seen near the inner edge of the ring current fluxes with variable, but generally reduced values in the ratio at the higher latitudes. This general characteristic has also been reported for ion fluxes precipitating from the 17-18 December 1971 magnetic storm [Sharp et al., 1976].

Comparisons of the H^+ and O^+ energy distributions in the region from $L=3$ to 4 are seen in Figure 5 for the 29 July 1977 and 29 December 1976 storms. Although differing in detail, the spectral features for the two storms are similar with the O^+ spectrums being significantly softer than the H^+ spectrums.

To further investigate the average energy characteristics at different times in the storm, the average energy of the fluxes, integrated over pitch angles, as a function of latitude was determined for each of the spacecraft passes shown in Figure 2. These results are seen in Figure 6 through 11. One particular feature of the average energy data stands out in the first three passes during the earlier portion of the storm. This feature is the pronounced dip in the average energy of the fluxes in the region of $L=4-4.5$. For the three passes later in the storm shown in Figures 9, 10, and 11, the average energy characteristics were quite variable with no systematic trends

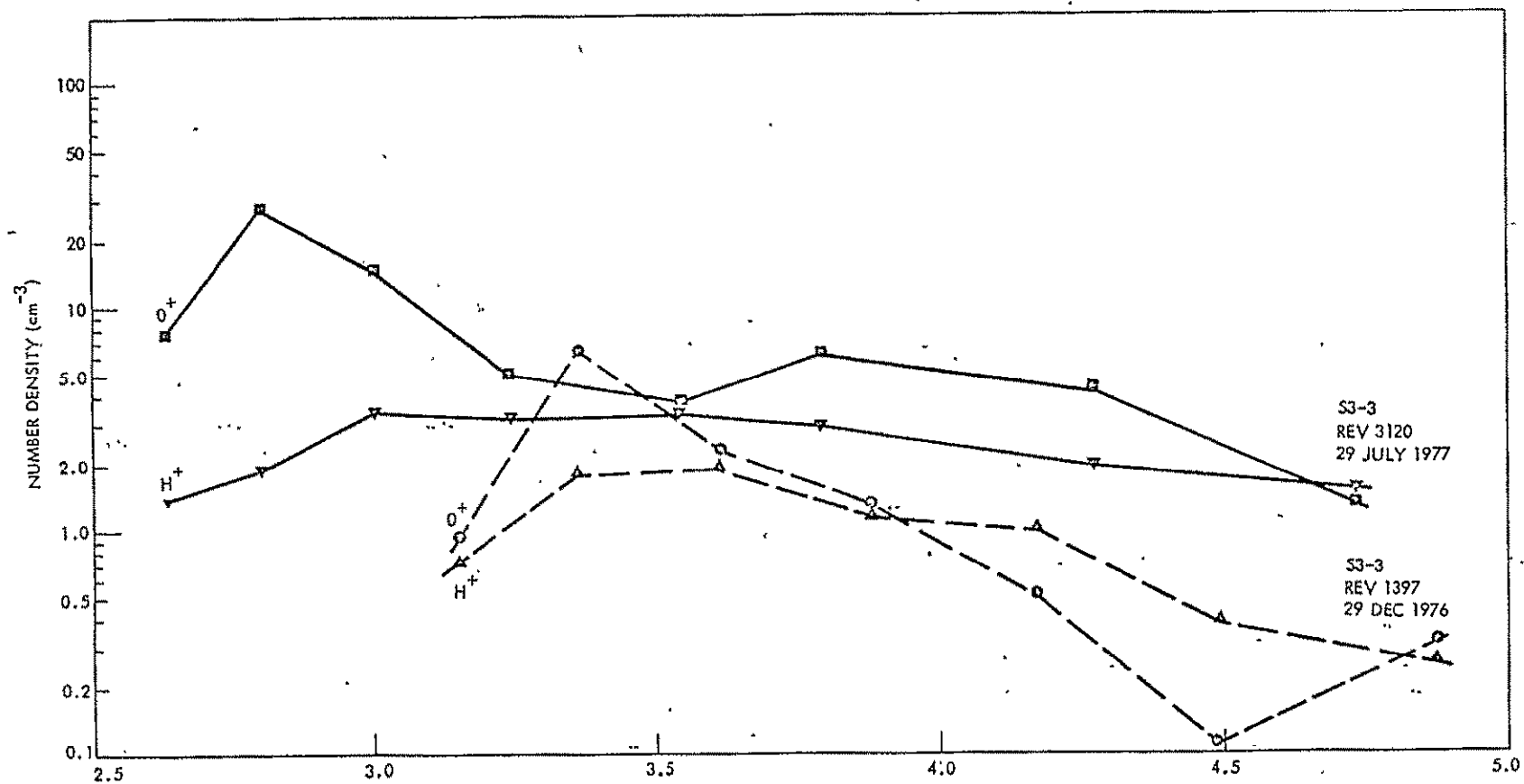


Figure 4. Number Densities for O^+ and H^+ During the 29 July 1977 and 29 December 1976 Magnetic Storms.

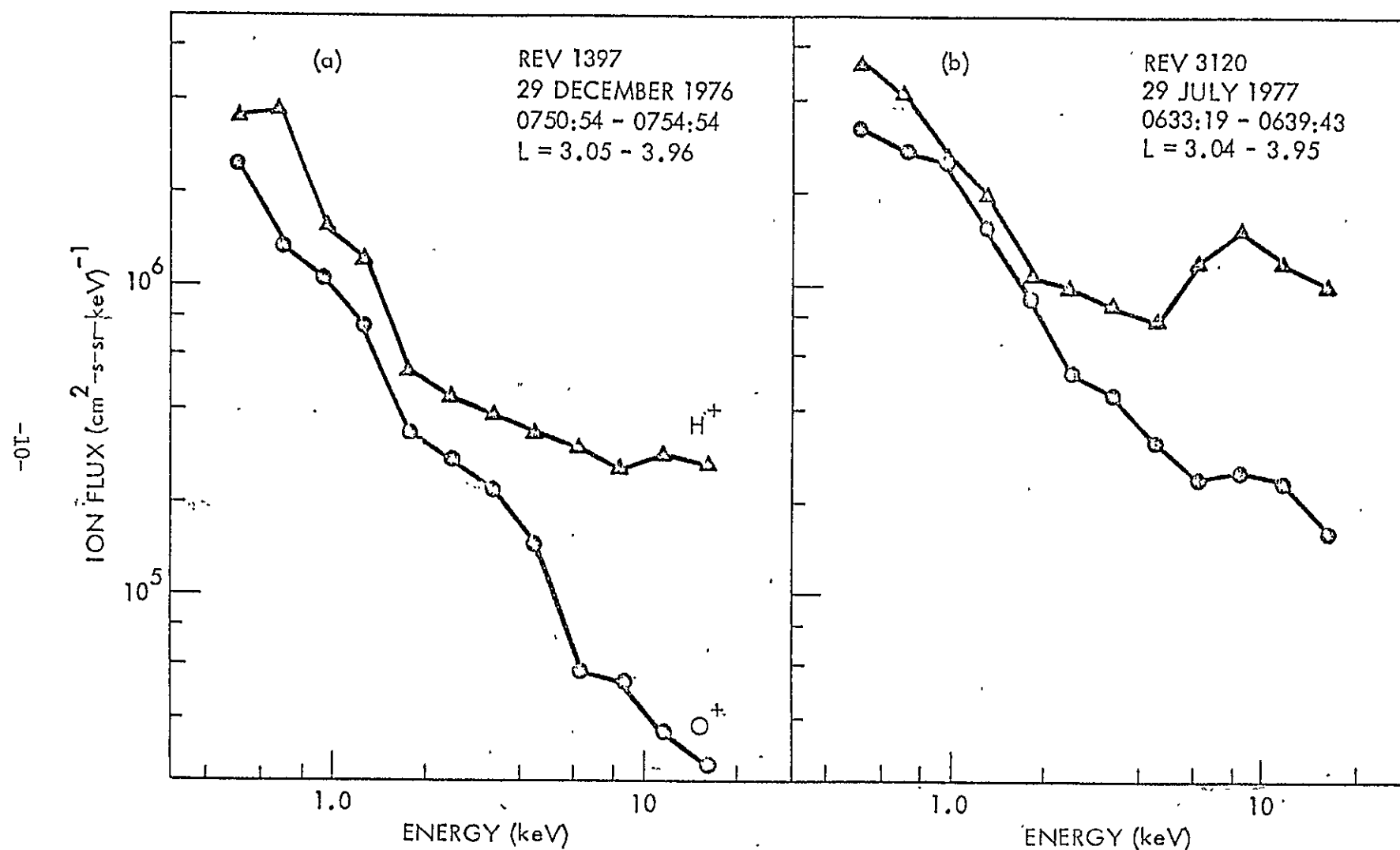


Figure 5. Energy Distributions for O^+ and H^+ Near the Peak of D_{ST} During the 29 July 1977 and 29 December 1976 Magnetic Storms.

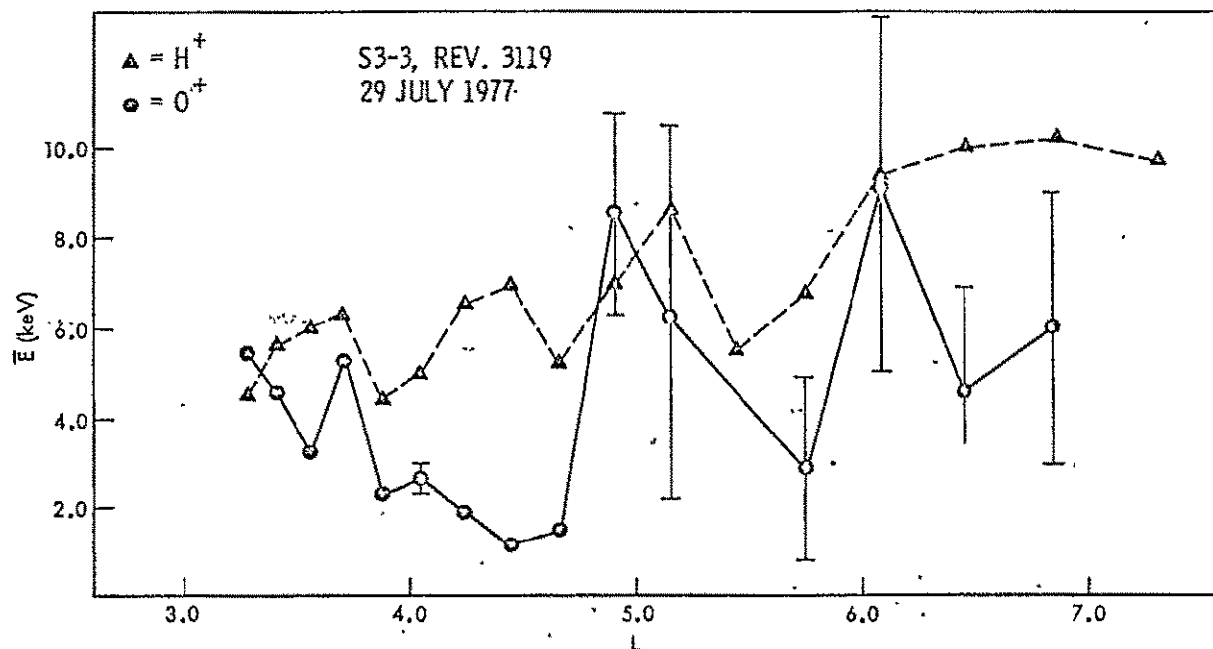


Figure 6. Average Energies of the O^+ and H^+ Ions During the Injection Phase of the 29 July 1977 Magnetic Storm.

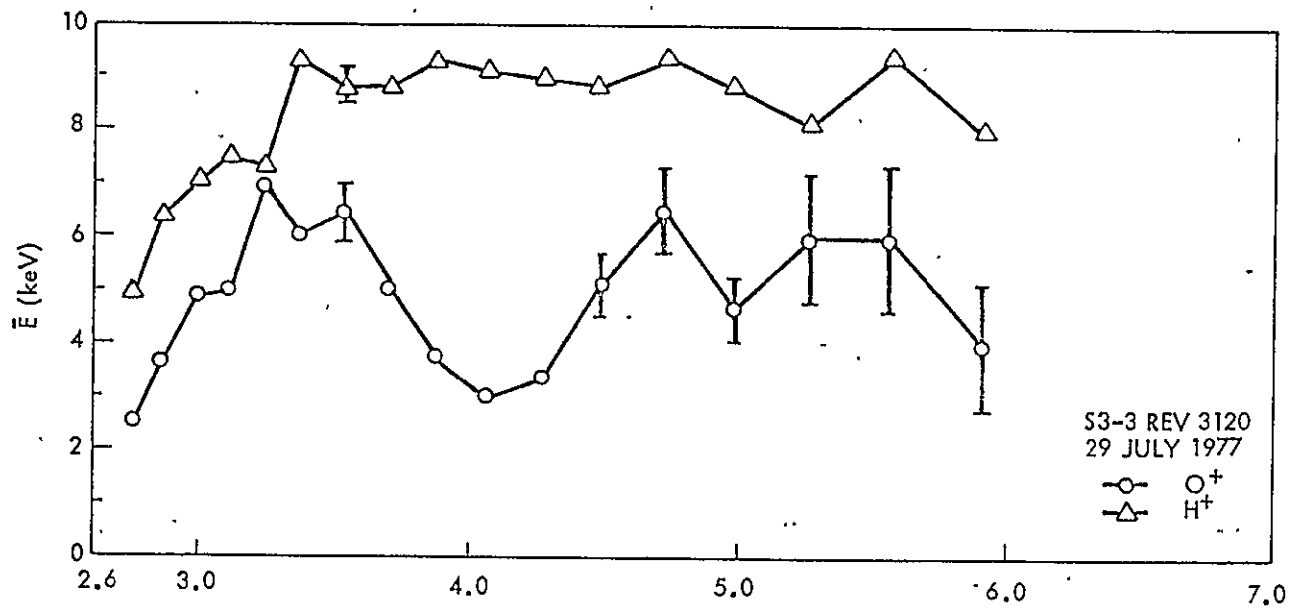


Figure 7. Average Energies of the O^+ and H^+ ions Near the Peak of the Main Phase of the 29 July 1977 Magnetic Storm.

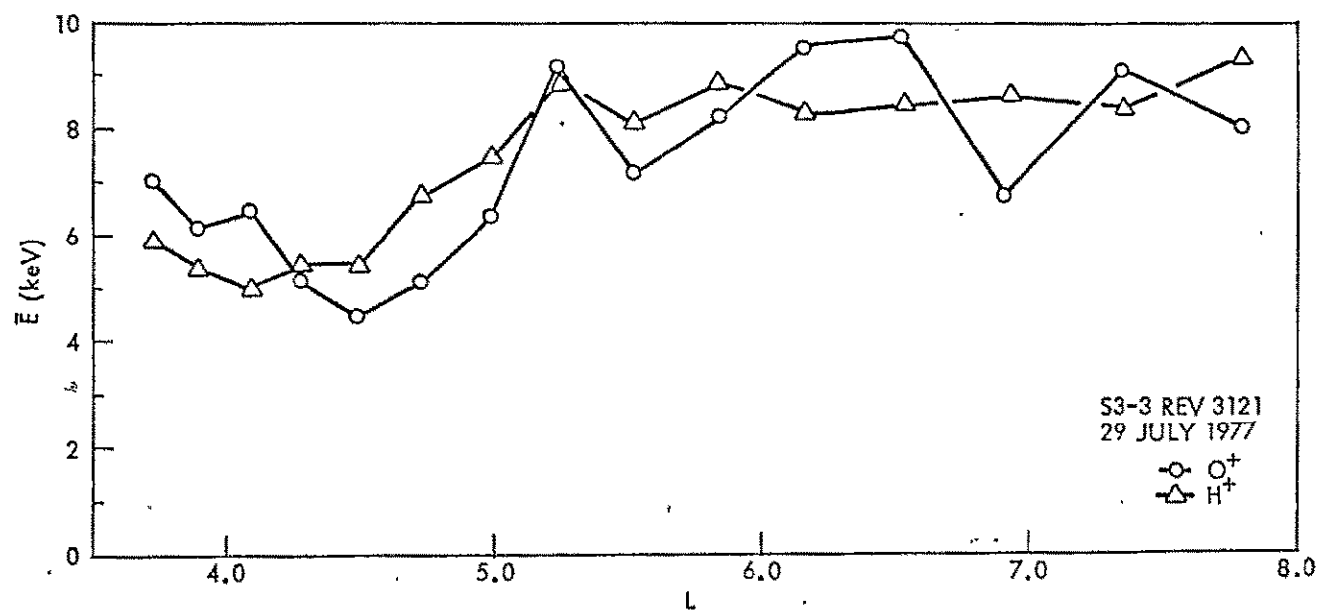


Figure 8. Average Energies of the O⁺ and H⁺ Ions Three Hours After the Peak of the Main Phase of the 29 July 1977 Magnetic Storm.

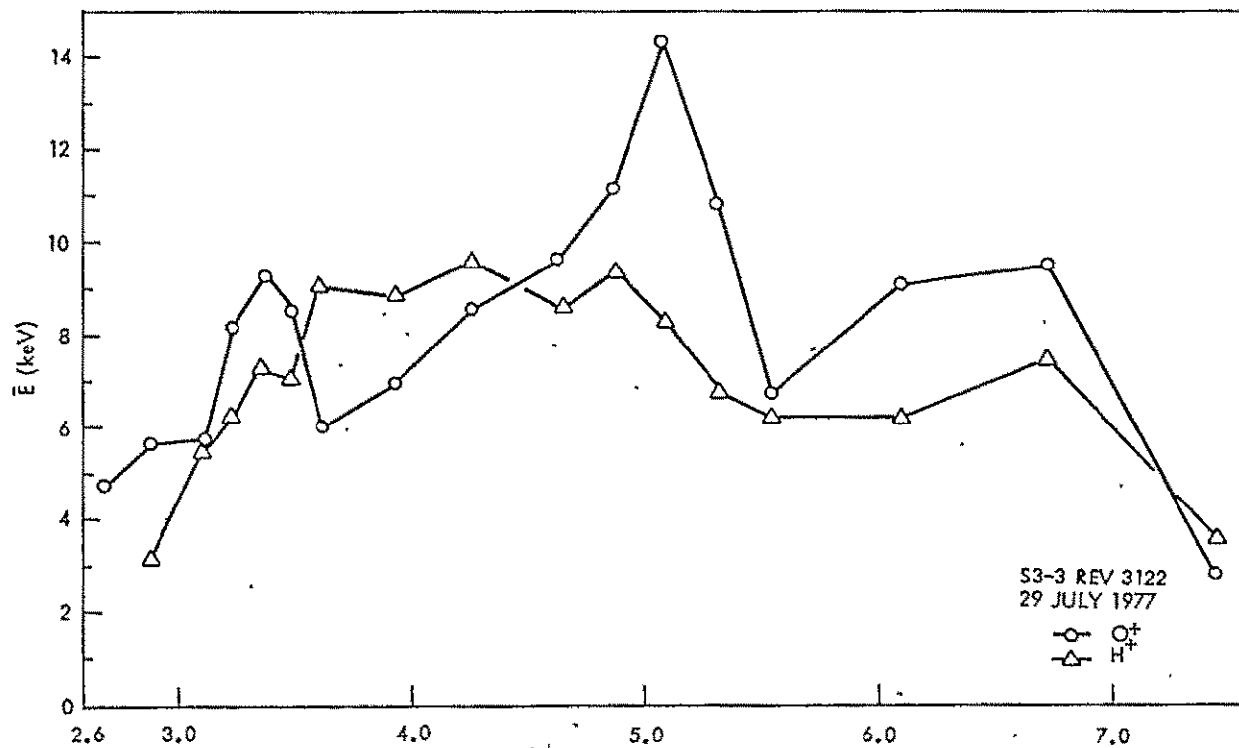


Figure 9. Average Energies of the O^+ and H^+ Ions Near a Secondary Peak in D_{ST} During the Early Recovery Phase of the 29 July 1977 Magnetic Storm.

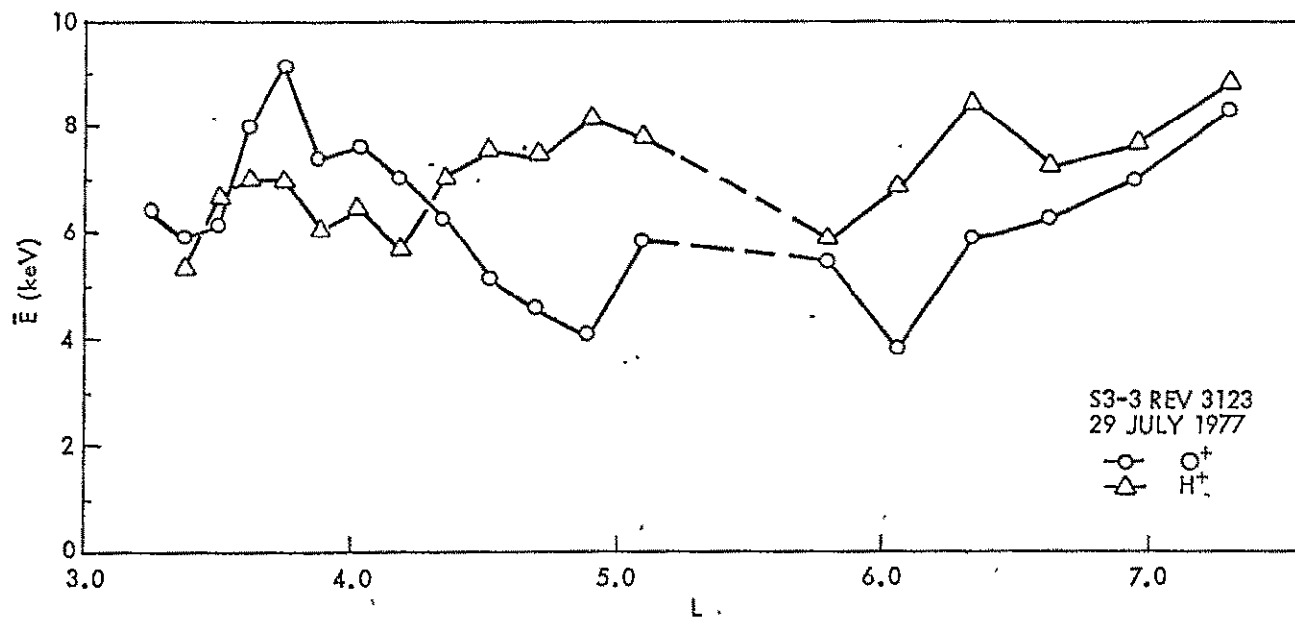


Figure 10. Average Energies of the O^+ and H^+ Ions During the Early Recovery Phase of the 29 July 1977 Magnetic Storm.

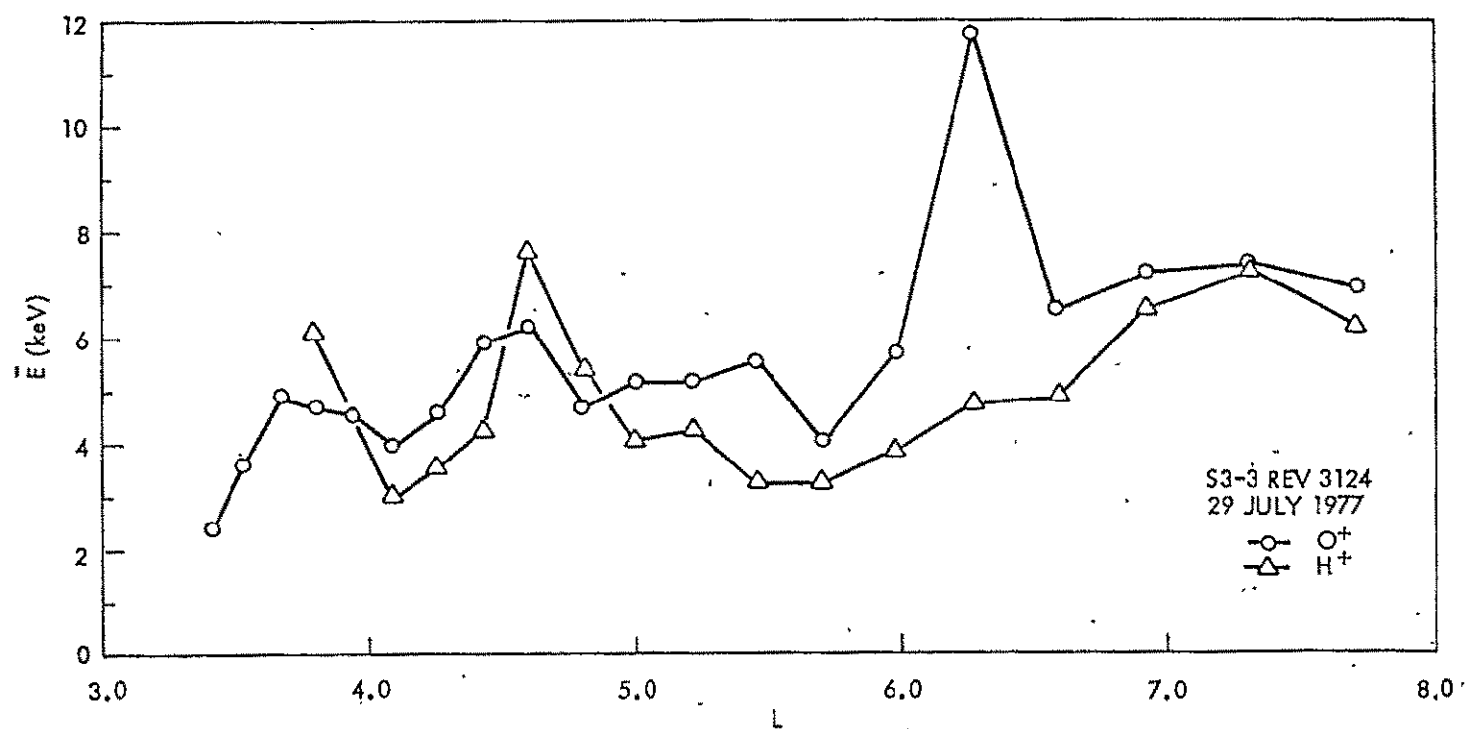


Figure 11. Average Energies of O^+ and H^+ Ions During the Early Recovery Phase of the 29 July 1977 Magnetic Storm.

in the average energy data being evident.

Evidence for conical pitch angle distributions of O^+ ions was found in the survey data for Revolution 3119 which was acquired (see Figure 2) during the ring current build up. Spin by spin plots of the pitch angle distributions at energies of 0.5, 0.68, 0.94 and 1.28 keV for 9 successive spins between $L=4.05$ and $L=4.45$ are shown in Figure 12 along with one spin at $L=4.66$. The loss cone regions between $\pm 15^\circ$ pitch angles is indicated by the cross hatching. The absence of upward streaming ions with fluxes peaked along the field direction in this Northern hemisphere pass is evident. However, significant fluxes of upward flowing conical distributions are easily identified along with weaker and less frequent fluxes of downward flowing conical distributions. Locally mirroring (90°) and precipitating (165° - 180°) fluxes of O^+ ions are seen to be very low or absent at these lower energies. At energies above 2 keV, trapped and precipitating O^+ and H^+ fluxes are observed in this same L -shell region. No significant fluxes of H^+ ions with conical pitch angle distributions were observed in this region. Large spatial and/or temporal variations in the upward flowing conical fluxes can also be seen in a single scan through the pitch angle range of the conical fluxes. This is seen in Figure 12 at 13857, 13872, 13889, and 13905 seconds. During the 5.4 seconds required for the pitch angle scans from 60° to 0° to 60° the spacecraft traveled about 25 km. Thus, spatial structures less than 25 km and/or temporal changes in less than 6 seconds are associated with the conical pitch angle distributions.

During REV 3119, significant fluxes of He^{++} were also observed at L -shells greater than $L=4$. Examples of the mass spectrum for three energy intervals in the range $L=4.0$ - 4.5 is shown in Figure 13. The He^{++} mass

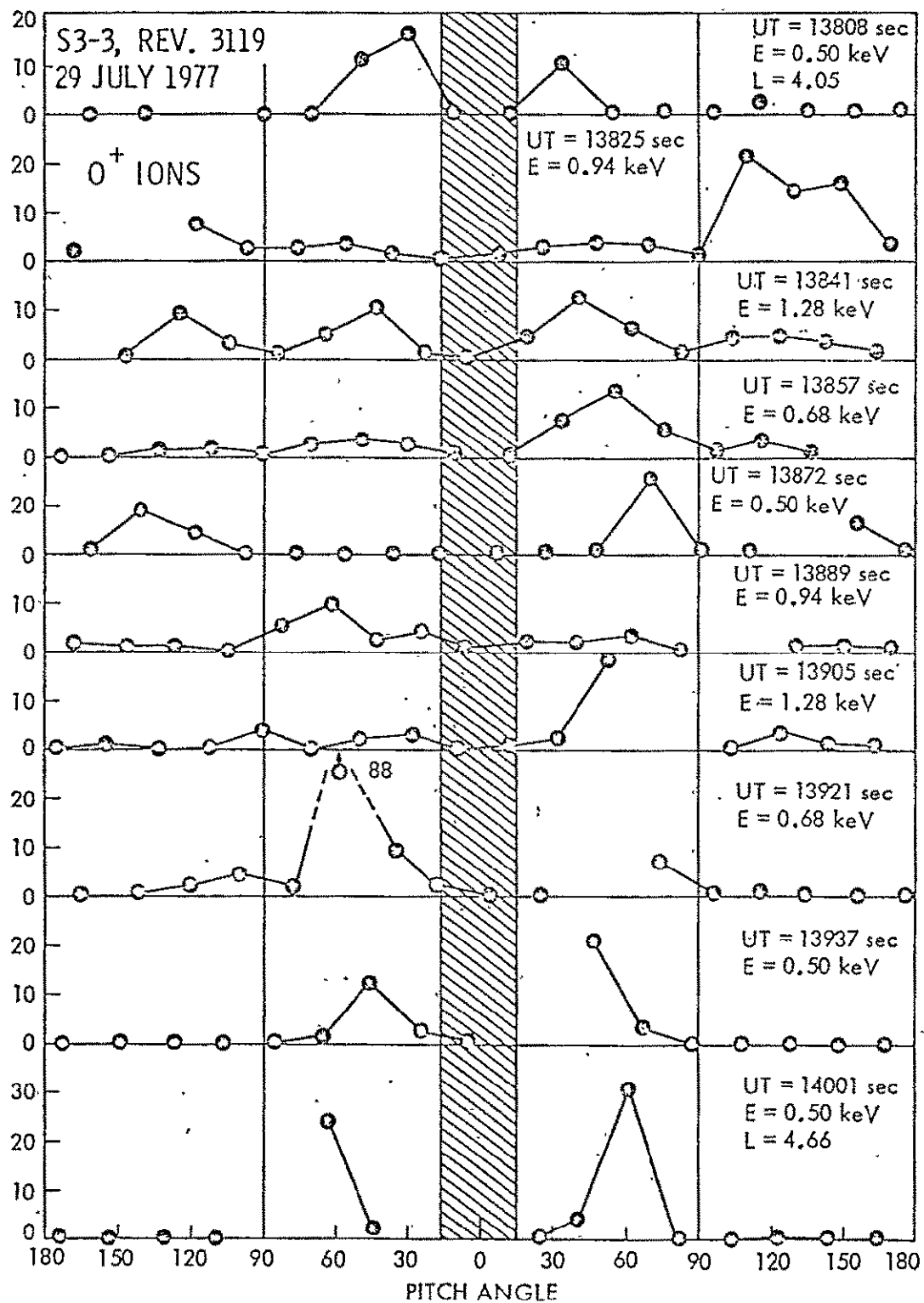


Figure 12. Conical Pitch Angle Distributions observed During the Injection Phase of the 29 July 1977 Magnetic Storm.

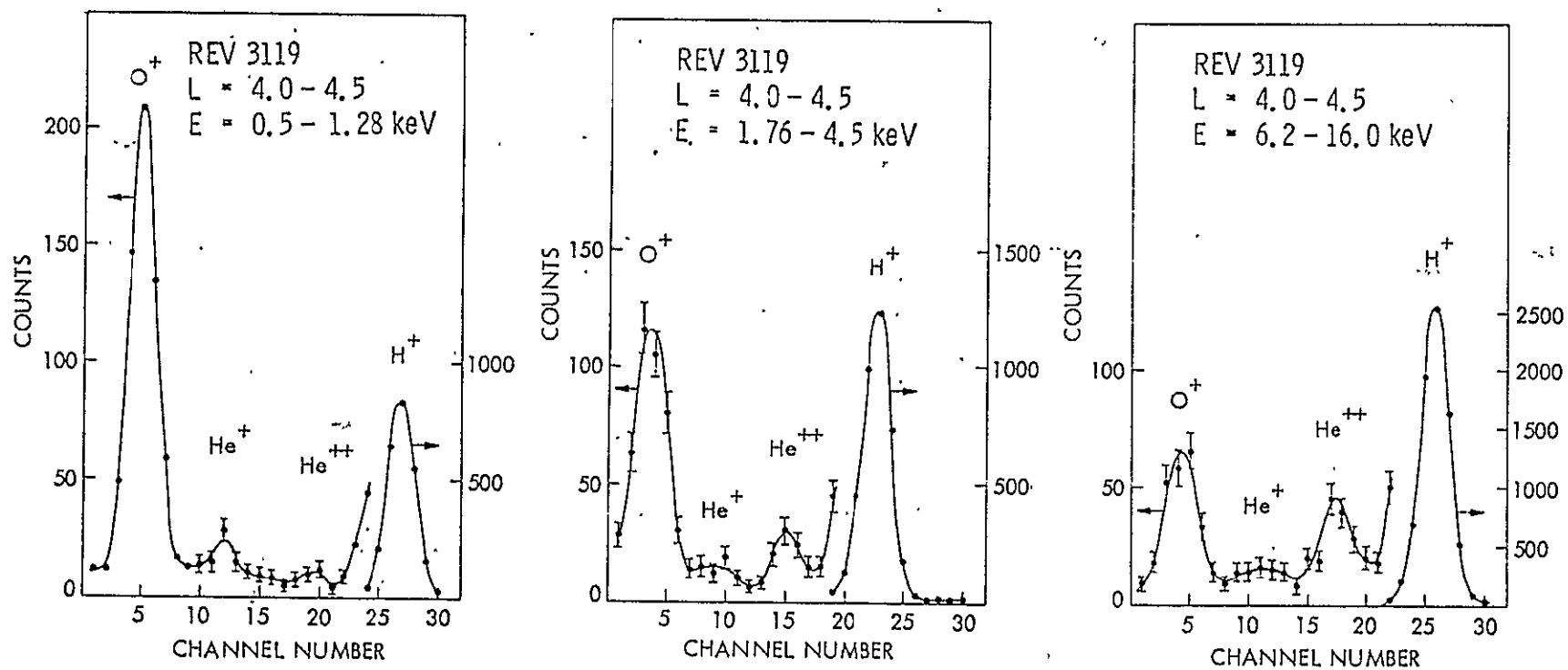


Figure 13. Mass Spectra Showing the Relatively Large He^{++} Fluxes in the L=4.0-4.5 Region During Injection Phase of the 29 July 1977 Magnetic Storm.

peaks are easily identified and are comparable with or larger than the He^+ intensities. The energy distributions for H^+ , O^+ , and He^{++} averaged over the region $L=4-6$ are shown in Figure 14. The O^+ spectrum is significantly softer than the H^+ and He^{++} spectrums which may indicate a different source region for the O^+ fluxes than for most of the H^+ fluxes.

The percentage of the H^+ fluxes found for the O^+ and He^{++} fluxes over the energy range of the instrument is shown in Figure 15. In the range $L=4-7$ the He^{++} is seen to be about 1-2 percent of the H^+ . The relatively high $\text{He}^{++}/\text{H}^+$ and $\text{He}^{++}/\text{He}^+$ ratios are incompatible with the ionosphere being the origin of He^{++} [Young et al., 1977] and thus it is concluded that the He^{++} ions are of solar wind origin (see Section 5 for discussion).

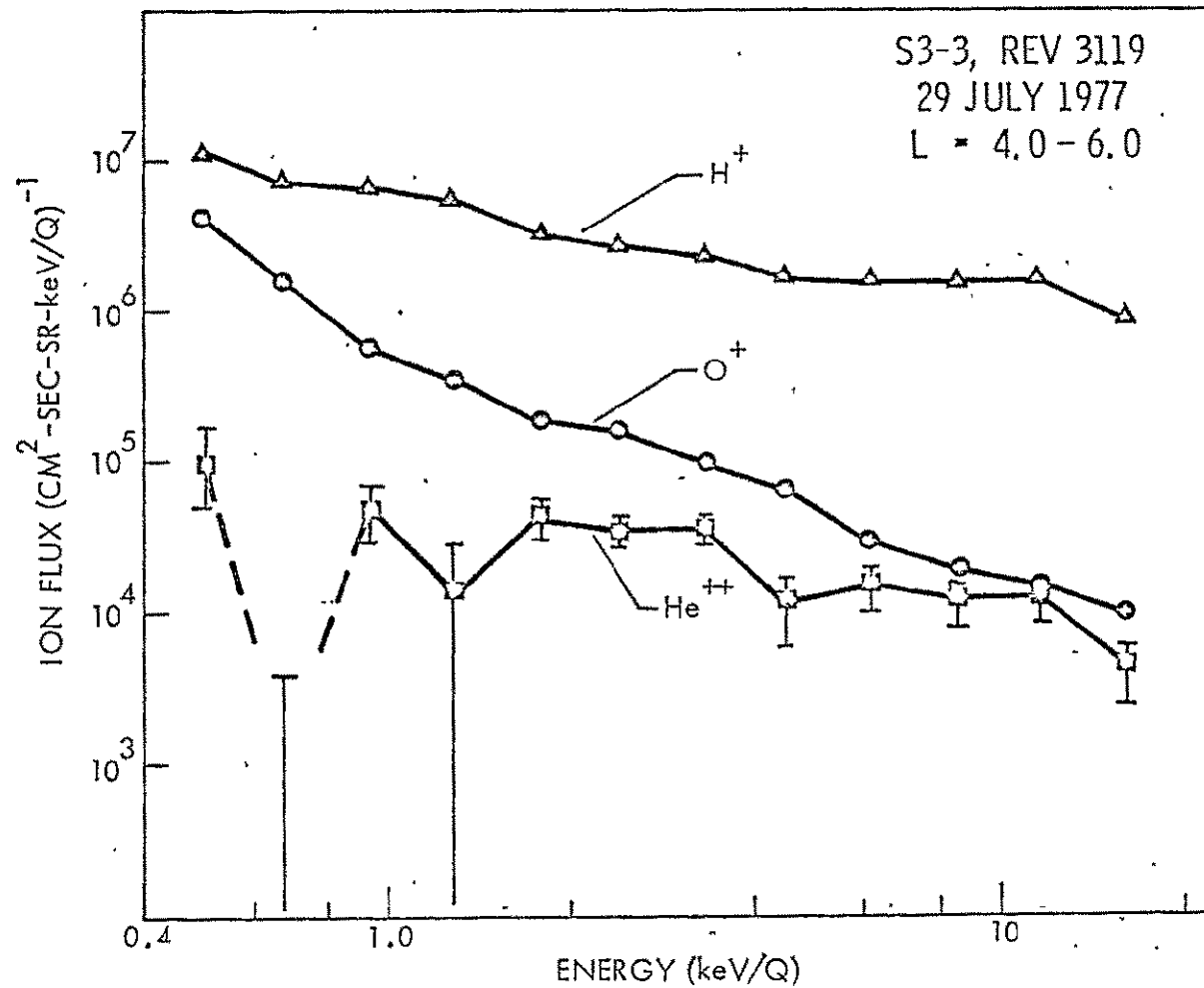


Figure 14. Energy Distributions of H^+ , He^{++} , and O^+ Fluxes During the Injection Phase of the 29 July 1977 Magnetic Storm.

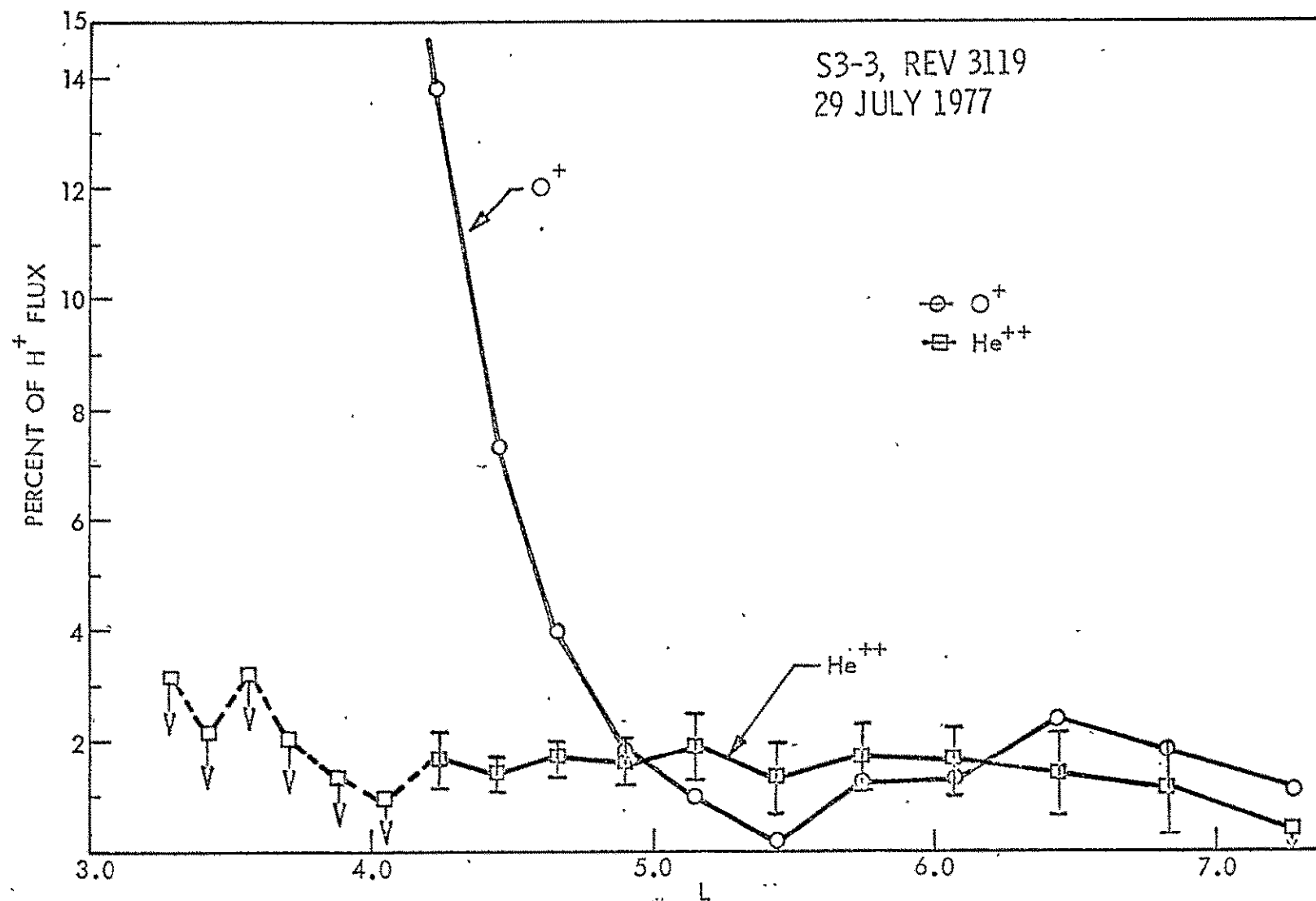


Figure 15. O^+ and He^{++} Fluxes Relative to the H^+ Fluxes During the Injection Phase of the 29 July 1977 Magnetic Storm.

SECTION 3

15 FEBRUARY 1978 MAGNETIC STORM

In the process of surveying data from magnetic storms that might be suitable for more concentrated investigations as part of the IMS, relatively large fluxes of He^{++} ions were also observed on REV 4773 during the injection phase of the 15 February 1978 magnetic storm. D_{ST} for this storm peaked at -188 at 1266 hour and the data for REV 4773 were acquired about 2 hours prior to the peak when D_{ST} was -83.

A survey plot of the data from REV 4773 in the L-shell range 4 to 7 is shown in Figure 16. The abscissa shows universal time (SYST), geographic longitude (LON), geographic latitude (LAT), spacecraft altitude (ALT), invariant geomagnetic latitude (ILA), and magnetic local time. The four lowest panels show the logarithm of the counts per half-second counting interval for the electron spectrometers with the lowest energy being CMEA, etc. The panel labelled PITCH shows the pitch angle of the look direction of the spectrometers. The next four panels show the logarithm of the counts from ions with $M/Q=1, 2, 4$, and 16 summed once per second from selected output channels from all three of the ion mass spectrometers, giving an approximate measure of the relative flux of the relevant species. The next three panels (CXA-1, CXA-2, and CXA-3 show the 32 point mass spectrums for each mass spectrometer at one of the four energy steps (for each spectrometer) indicated by the short bars in the "discretes" panel. The energy step code is no bar for step #1, a double bar for step #2, a single bar above the baseline for step #3, and a single bar on the baseline for energy step #4. These steps correspond

S3-3, REV 4773
15 FEBRUARY, 1978

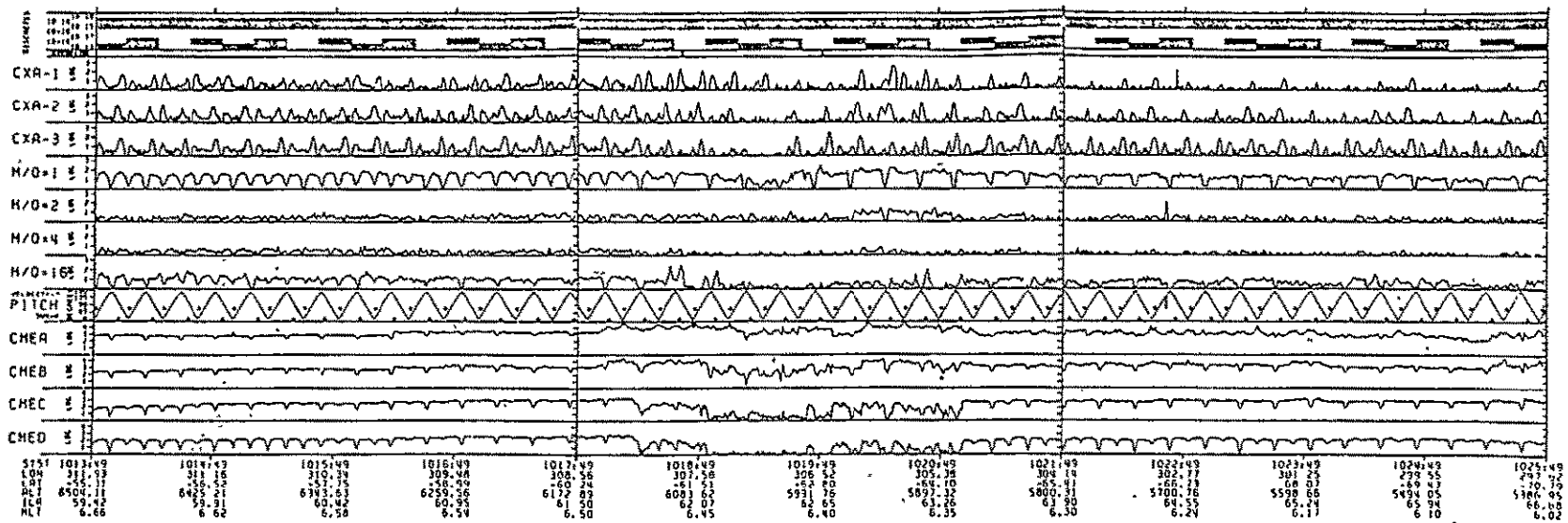


Figure 16. Survey Plot of Ion and Electron Data from the S3-3 Satellite During the Injection Phase of the 15 February 1978 Magnetic Storm.

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sequentially to the four energies for each spectrometer as discussed in the Introduction.

Two characteristics of the data particularly relevant to this report are evident in Figure 16. Large upward streaming conical distributions of O^+ ions (and some H^+ ions) are seen in the time interval between 1017:49 and 1021:49. Also, by comparing the $M/Q=2$ (He^{++}) response with the $M/Q=1$ (He^+) response in the time interval 1017:49 to 1025:49 and by looking at the mass spectrums in this interval, evidence for significant He^{++} ions is found. Most of the $M/Q=1$ and $M/Q=2$ response in the time interval between 1013:49 and 1017:49 is due to background counts which has been determined by detailed analysis of the responses between the peaks in the mass spectrums. Examples of the mass spectrums when summed over the energy steps for each spectrometer in the range $L=4-7$ are shown in Figure 17. The relatively large He^{++}/He^+ flux ratios should be noted. Figure 18 shows the He^{++} percentage of the H^+ flux in the energy range of the instrument, and the He^{++}/H^+ ratio of the average phase space density over the same measured velocity ranges (0.5-8 keV/Q for H^+ and 1.0 to 16 keV/Q for He^{++}). These relatively high values are compatible with solar wind origin for the He^{++} ions and are incompatible with ionospheric origin for the He^{++} ions. Also it is seen that significant He^{++} fluxes are measurable as low as $L=3.9$. Large background counts limit the sensitivity to He^{++} ions below $L=3.9$.

S3-3, REV 4473
15 FEBRUARY 1978

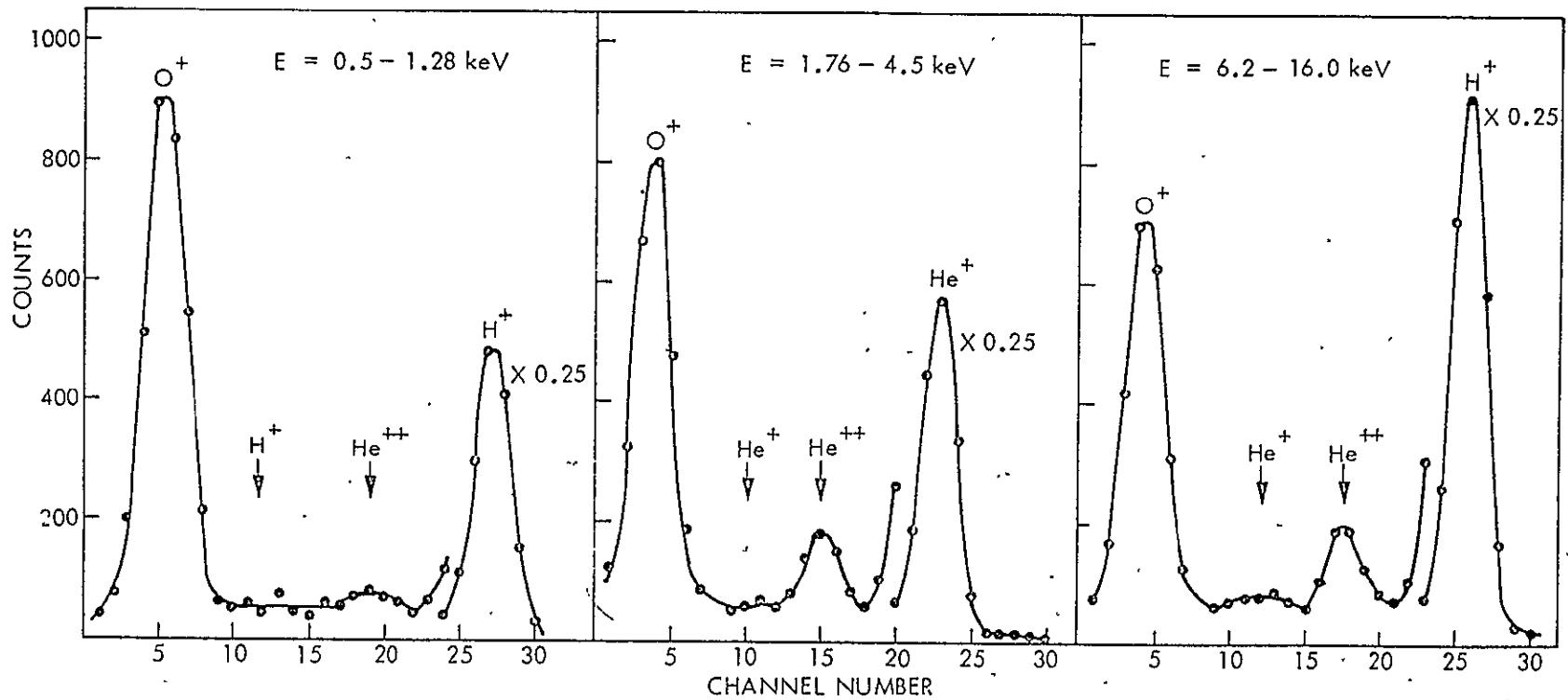


Figure 17. Mass Spectrums Showing the Relatively Large He^{++} Ion Fluxes in the $L=4-7$ Region During the Injection Phase of the 15 February 1978 Magnetic Storm.

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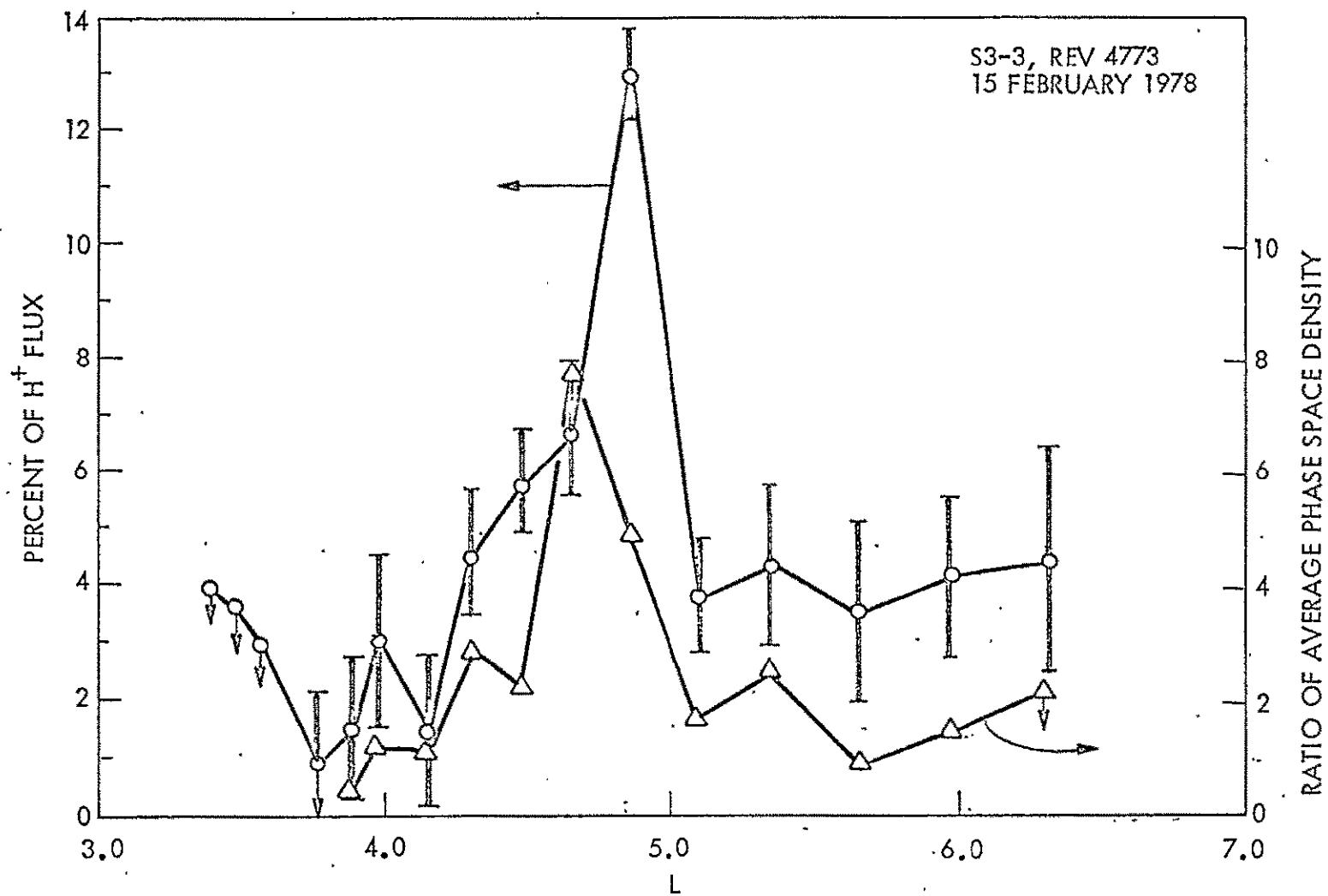


Figure 18. The He^{++} Percentage of the H^+ Flux and the He^{++}/H^+ Ratio of Average Phase Space Density During the Injection Phase of the 15 February 1978 Magnetic Storm:

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SECTION 4

GEOMAGNETIC STORMS FOR IMS

In support of the International Magnetospheric Workshops at Innsbruck, Austria in June 1978, preliminary ion composition data from four magnetic storms were prepared and presented. These storms were on 29 July 1977, 23 September 1977, 2 December 1977, and 11 December 1977. Except for the 29 July storm, further analysis of these events has not been pursued under this program. The Workshops were held to present preliminary IMS data and then to select some time periods for more detailed study. The time periods selected for the more detailed IMS studies were associated with the 2 December storm as the primary event and the 11 December storm as the secondary event.

Moderately good data coverage for the 2 and 11 December storms was obtained with the S3-3 spacecraft in the ring current regions in the midnight sector. D_{ST} and the general location of S3-3 data acquisitions for these storms are shown in Figures 19 and 20. For each storm, data are acquired during the injection phase, within 3 hours of the peak of the main phase, and during the recovery phase.

Three examples of the data during orbit revolutions (REV) 4151, 4153, and 4156 from the 2 December storm are shown in Figures 21, 22, and 23 for the inner ($L < 4$) ring current regions. The data are in the same format as for Figure 16. The data from REV 4151 seen in Figure 21 were acquired during the injection phase when D_{ST} was approximately half of its peak value.

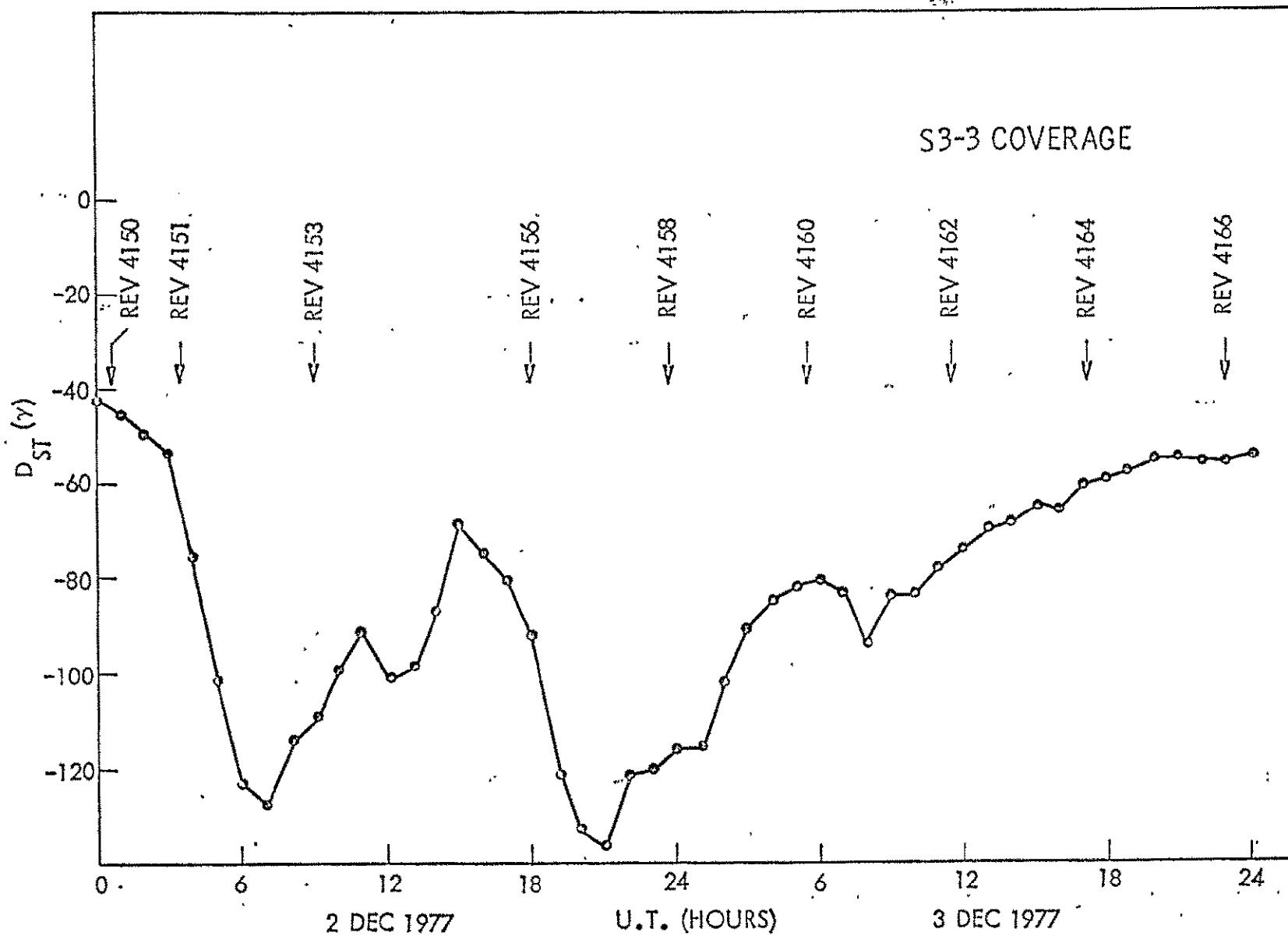


Figure 19. Distribution of the S3-3 Satellite Data Acquisitions During the 2 December 1977 Magnetic Storm.

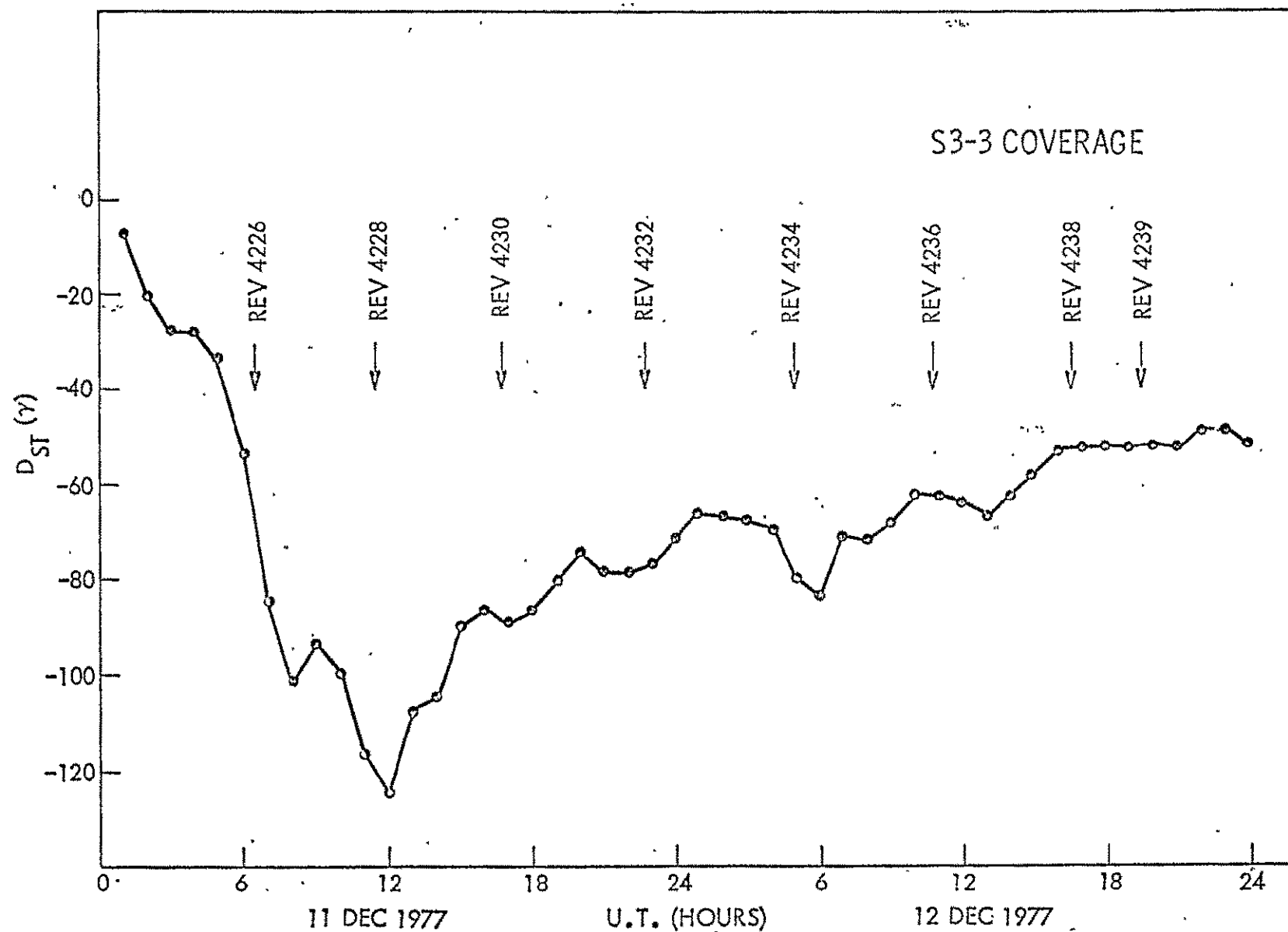


Figure 20. Distribution of the S3-3 Satellite Data Acquisitions During the 11 December 1977 Magnetic Storm,

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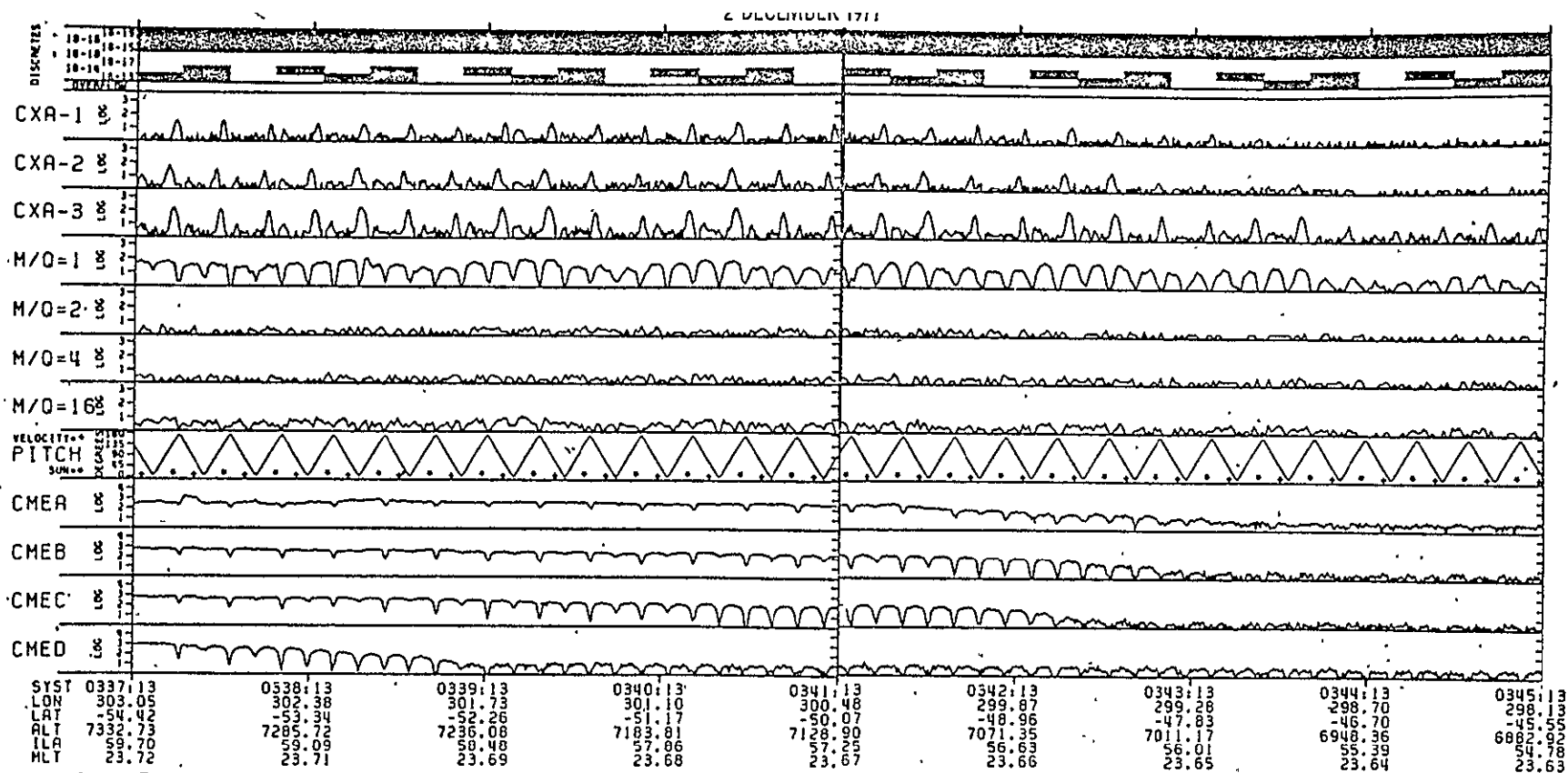


Figure 21. Survey Plot of S3-3 Ion and Election Data During the Injection Phase of the 2 December 1977 Magnetic Storm.

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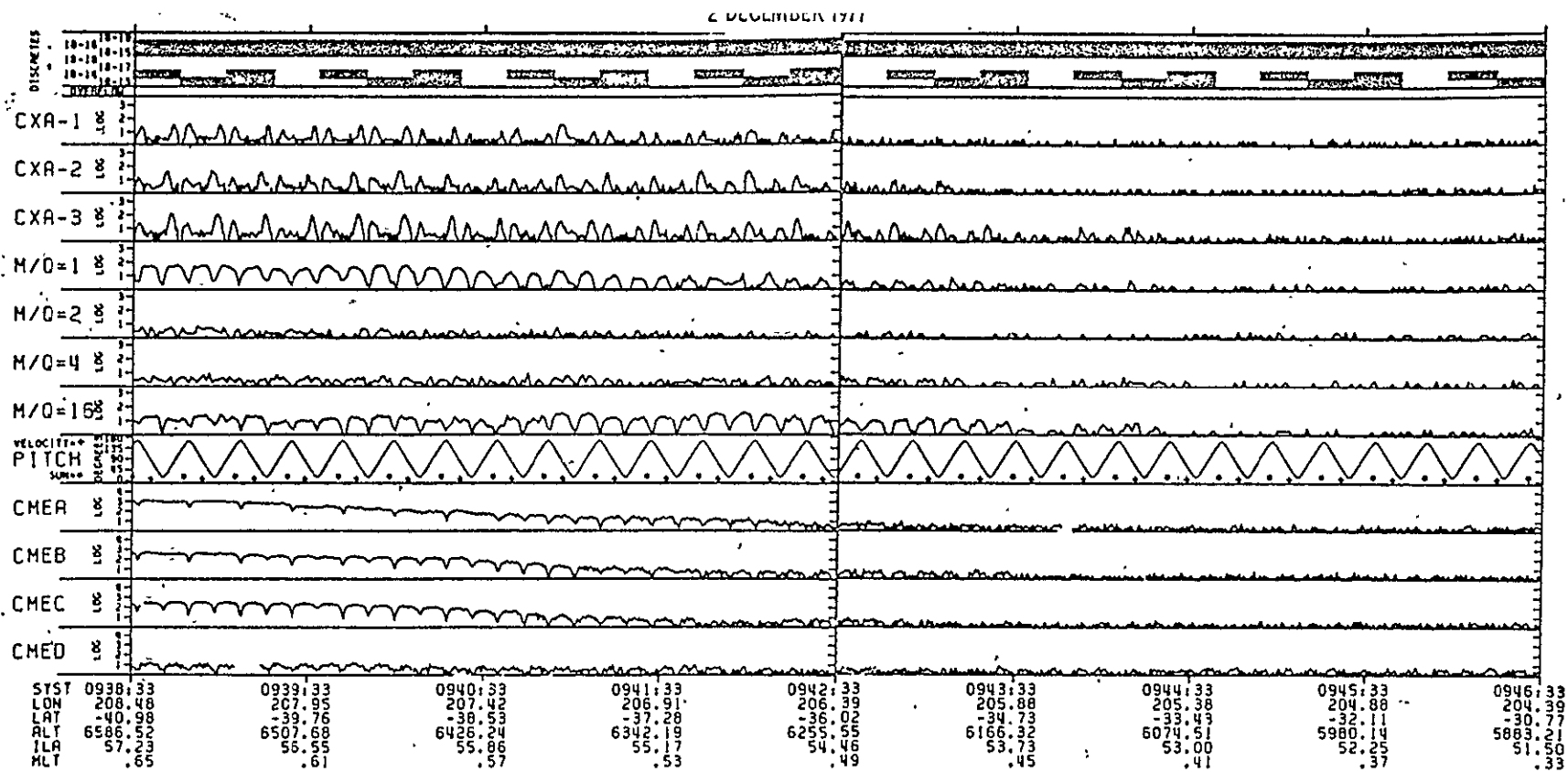


Figure 22. Survey Plot of S3-3 Ion and Electron Data Near the Main Phase Peak of the 2 December 1977 Magnetic Storm.

S3-3, REV 4156
2 DECEMBER 1977

-33-

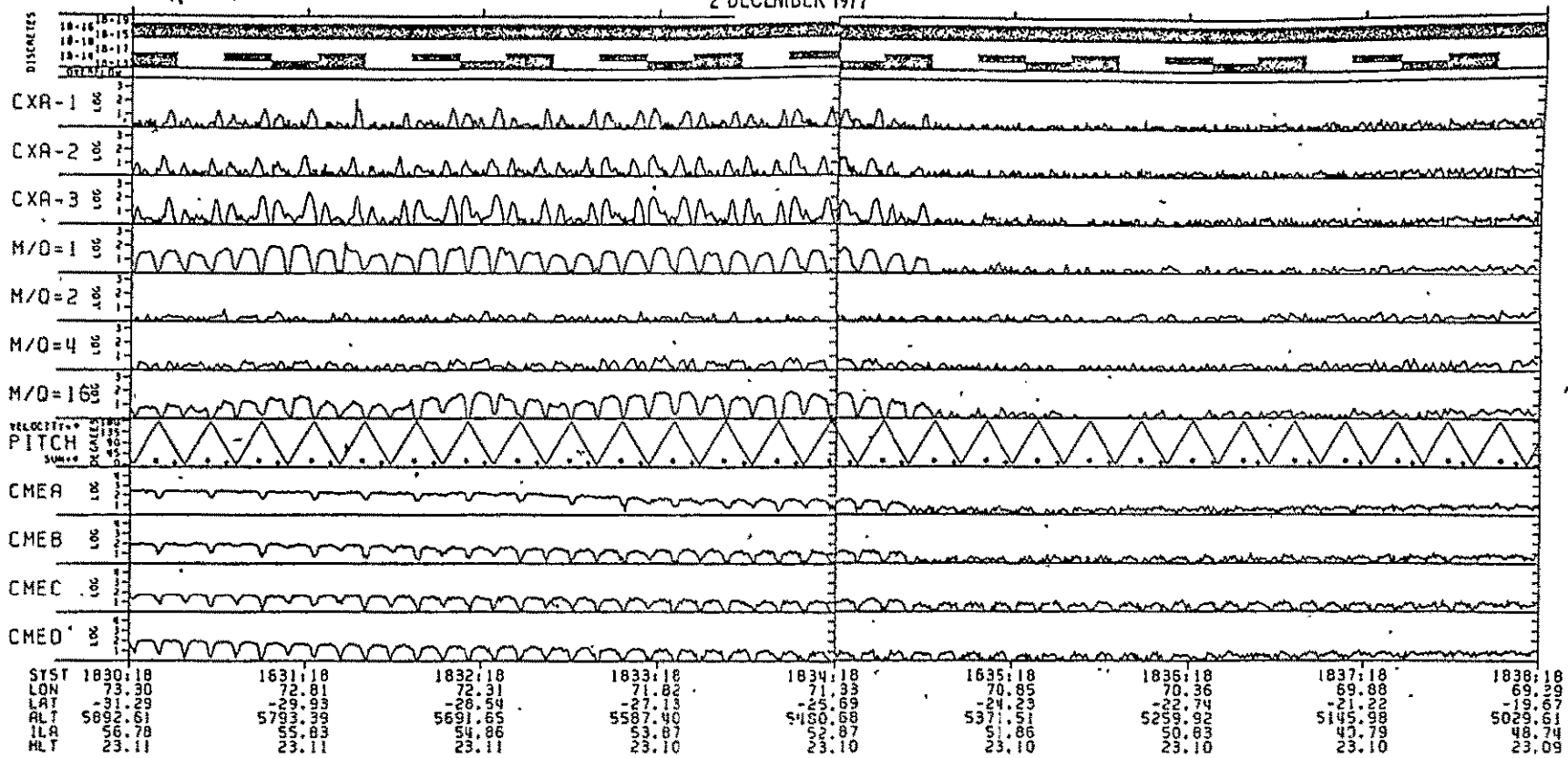


Figure 23. Survey Plot of S3-3 Ion and Electron Data During the Second Ring Current Injection Event of 2 December 1977 Magnetic Storm.

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Relatively large H^+ fluxes compared to the O^+ are found at this phase of the storm in the midnight sector. The moderately large H^+ fluxes extend down to an invariant magnetic latitude (ILA) of about 55.7° ($L=3.1$). During the next S3-3 data acquisition period (REV 4153) data are acquired within 3 hours of the peak of D_{ST} . These data for $L<3.5$ are seen in Figure 22. The O^+ fluxes are now found to be comparable to the H^+ fluxes and extend down to an invariant latitude of 53° ($L=2.8$). Data shown in Figure 23 from REV 4156 were acquired during a second ring current injection and the ion composition can be seen, by comparison with Figure 21, to be quite different from the first injection event. The O^+ flux is comparable to the H^+ flux and evidence for He^+ ions can be seen in the CXA-3 mass plot and in the $M/Q=4$ response plot.

An example of data during the main phase of the 11 December storm is shown in Figure 24 primarily to indicate evidence for a pitch angle scattering process that is ion mass selective. This can be seen in Figure 24 by comparing the $M/Q=1$ response, the $M/Q=16$ response, and the pitch angle (PITCH) of the instrument look direction in the time period from 1200:22 to 1205:30. Loss cones for the H^+ ions in this region are generally well developed in both directions along the magnetic field; whereas, for the O^+ ions the loss cone region near 0° pitch angle (instrument pointed upward) contains high fluxes, and in some regions, nearly isotropic fluxes. At this stage of analysis of these types of events, it appears likely that strong pitch angle scattering is occurring above the satellite for the O^+ ions, but not for the H^+ ions. The precipitation of these large fluxes of O^+ ions down to 56° magnetic latitude is expected to produce strong heating at F-region altitudes. Coordinated IMS investigations of this event

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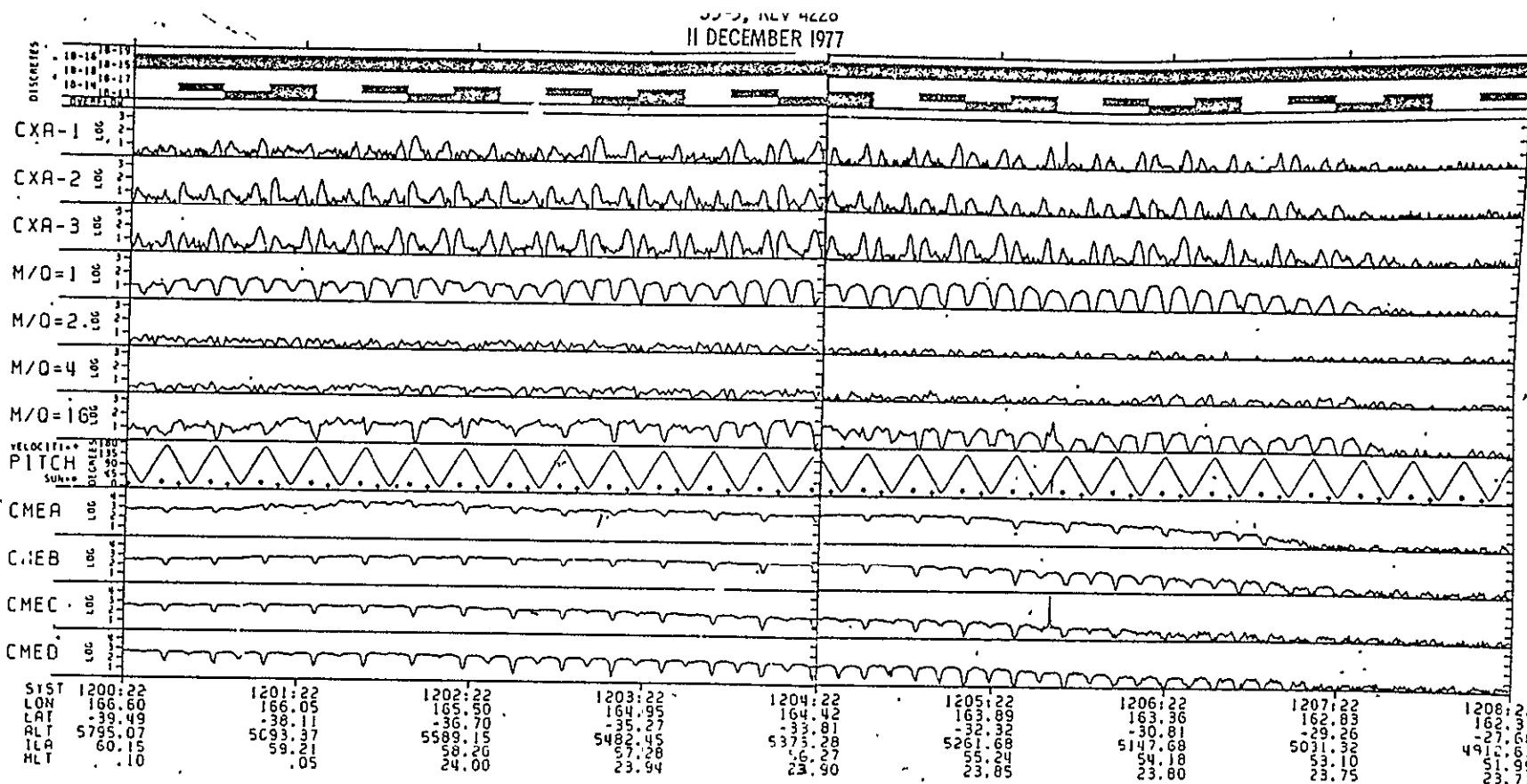


Figure 24. Survey Plot of S3-3 Ion and Electron Data During the Main Phase of the 11 December 1977 Magnetic Storm. Large Fluxes of Precipitating O^+ Ions Are Observed from 1200:22 to 1204:30 U.T.

could contribute to a better understanding of this energy dissipation in the upper atmosphere and ionosphere.

The data from REV 4228 shown in Figure 24 were acquired at the peak of the main phase of the storm. The large O^+ fluxes observed throughout the L-shell region from 2.7 to 4.0 (ILA=53-60°) indicate that the ionosphere is a significant contributor to the ring current fluxes in the energy range from 0.5 to 16 keV.

For the 2 and 11 December storms, preliminary information was also presented at the IMS Workshop at Innsbruck, Austria, on the location of the dayside cusp, the inner edge of the ring current, and the polar cap boundary as determined from the ion composition experiment on the S3-3 spacecraft.

SECTION 5

DISCUSSION AND CONCLUSIONS

Although the dynamic nature and local time asymmetries of the ring current during the main phase of a magnetic storm make storm-to-storm comparisons difficult, some similarities between data taken near the peaks of the main phases of the storms on 29 July 1977 and on 29 December 1976 are noteworthy. The magnetic local time for the 29 July 1977 data is near 0500 hours and for the 29 December 1976 data is near 0200 hours. As seen in Figure 5, the average energy distributions for the O^+ ions in both storms are significantly softer than for the H^+ ions in the $L=3-4$ range. This was true at this time at all L -values below 6.0 for the 29 July storm as seen in Figure 6. This perhaps is indicative of different source regions for the O^+ and H^+ ions at this local time and phase of the storm. In addition, as seen in Figure 4, the O^+ number density significantly exceeds the H^+ number density within the instrument energy range near the inner edge of the ring current in both of the storms. A similar trend for the precipitating fluxes also observed in the local morning sector during the 17-18 December 1971 magnetic storms has been reported by Sharp et al., 1976. Thus it appears that this is at least a commonly occurring feature during the main phase of storms in the local morning sector.

As noted in Section 2, the data on the average ion energies presented in Figures 6, 7, and 8 for the 29 July 1977 storm show a rather dramatic drop in the average O^+ ion energies in the region of $L=4-5$. This is just the region of upstreaming low energy O^+ ions seen in Figure 12 during the injection phase of the storm. These ions are at sufficiently high pitch angles to be trapped, and in a few cases in Figure 12, downward moving

trapped O^+ ions are also seen. Trapped energetic electrons are observed at higher L-values on this same pass, strongly indicating that the upward flowing O^+ ions are on closed field lines and thus are becoming a part of the ring current at these low L-shells. This mechanism of direct injection of low energy ionospheric ions into the ring current at low L-shells can then account for the low average O^+ energies in the L=4-5 regions observed in the data presented in Figures 6, 7, and 8. The fact that upstreaming ions are not observed in the L=4-5 regions for REV 3120 and 3121 could result from temporal or local time variations..

This mechanism of direct injection of ionospheric ions into the ring current at low L-shells is also supported by the S3-3 observations prior to the main phase peak of the 15 February 1978 storm. As noted earlier and as seen in Figure 16, upward flowing conical distributions of O^+ and H^+ ions are observed. The most prominent upward flowing ions are in the L=4.5 to 5.1 region and are at trapped pitch angles. Again, trapped energetic electrons are observed at higher L-shells, strongly indicating that the upward flowing O^+ ions are on closed field lines.

The large fluxes of O^+ ions observed in the ring current during the magnetic storms discussed in this report and during storms previously reported on [Johnson et al., 1979, and Geiss et al., 1979] show that the ionosphere is a major contributor to the ring current ions in the energy range of the S3-3 satellite measurements (0.5-16 keV). The contribution of solar wind ions to the ring current during magnetic storms can be assessed from observations of the ratios of the He^{++}/H^+ and He^{++}/He^+ intensities since the He^{++}/H^+ flux ratio in the solar wind is relatively large (typically about 5×10^{-2}) whereas the He^{++}/H^+ and He^{++}/He^+

He^+ flux ratios for the ionospheric components found in the outer magnetosphere by Young et al., (1977) are relatively small ($\sim 10^{-3}$ and $\sim 10^{-2}$, respectively).

For the 15 February 1978 magnetic storm, it can be seen from Figure 18 that the $\text{He}^{++}/\text{H}^+$ flux and phase space density ratios in the $L=4-6$ region are typically greater than 10^{-2} and from Figure 17 that the $\text{He}^{++}/\text{He}^+$ flux ratio will be greater than 1.0 in a comparable L-shell region. These ratios are consistent with solar wind origin and inconsistent with ionospheric origin for the He^{++} ions.

For the 29 July 1977 storm, the $\text{He}^{++}/\text{H}^+$ flux ratios, as seen in Figure 15, are typically $1-2 \times 10^{-2}$ in the $L=4-7$ region. The He^{++} fluxes in the $L=4.0$ to 4.5 region can be seen from Figure 13 to be comparable to, or larger than the He^+ fluxes. These data are also consistent with solar wind origin, but not with ionospheric origin for the He^{++} ions.

The preliminary investigations of the 2 and 11 December 1977 magnetic storms support the conclusions of the IMS Steering Committee that these storms are good candidates for detailed and coordinated investigations by the IMS community. From the point of view of ring current composition, they appear to exhibit some interesting and perhaps unique composition features for which adequate data exist to merit detailed analysis.

SECTION 6

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